Distributed renewable energy generation: a critical review based on the three pillars of sustainability

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Abstract: Reducing emissions responsible for the climate change is recognized as a strategic goal at European and global level. A higher deployment of renewable energy sources is considered as essential for a low-carbon transition, towards a more sustainable energy system. The 2030 Framework for Climate and Energy sets out the European Union target for 2030 of at least 27% for the share of renewable energy consumption. A high share of renewables requires a new flexible and integrated electricity system to ensure grid stability and match supply and demand.
The advances in technologies for renewable electricity and heating production, efficient storage solutions, and advanced ICT allow flexible electrical infrastructures: distributed renewable energy generation is now widely recognized as the main pathway towards an effective integration of discontinuous sources into the energy system.

The discussion on renewable energy sources introduction in the energy system has long been focused on technical, economic and policy issues, but the transition to a distributed renewable energy generation approach demands a change of perspective, considering a multi-sectoral sustainability view and the need for multi-stakeholder action. Purpose of this research is reviewing the more recent scientific papers on the distributed renewable energy generation approach, focusing on how all the three key sustainability dimensions, environmental, economic and social, are evaluated and managed in a multi-criteria perspective. The sustainability indicators suggested in literature are classified and discussed to build up an up-to-date and comprehensive set of sustainability related criteria, suitable for future research applications and for supporting decision making processes.

Keywords: Distributed generation, Renewable energy, Sustainability, Multi-criteria analysis

1. Introduction

Since European Union (EU) countries agreed measures to support the transition to a more competitive, secure and sustainable energy system, while mitigating climate change through the reduction of greenhouse gas (GHG) emissions (*Energy Roadmap to 2050*), good progress have been achieved in energy efficiency targets and improved energy use from renewable sources (Chapman and Itaoka, 2018). The EU 2030 Framework for Climate and Energy, strengthen the EU long-term strategy in renewable energies, setting out the target of at least 27% for the share of renewable energy consumed in the EU in 2030.

The variability of many renewable energy sources together with technologies high costs have been for long time the main concern questioning the convenience of integrating such sources in the electricity system. Fostered by technologies costs reduction, incentives such as feed-in-tariffs and energy policies supporting low environmental impact solutions (Chapman and Itaoka, 2018), according to the International Renewable Energy Agency (IRENA) statistics the globally renewables installed capacity increased from about 990 GW in 2007 to about 2006 GW in 2016 and the trend forecasted by the International Energy Agency (IEA) shows strong growth through 2022, with an increase of over 950 GW respect to current capacity.

The new integrated system brings along the widening of the energy stakeholders' community: through the decentralized energy production, "consumers" (both households and businesses) will be called to a more active role along the energy value chain as "prosumers", being simultaneously energy producers and consumers.

The transition to a more sustainable energy system is then to be considered from this new perspective, that requires a wider multi-level approach and a comprehensive sustainability view.

This paper presents the main results of a review of the current scientific literature concerning the clean energy transition through distributed renewable energy generation, from an exhaustive sustainability viewpoint: we focused our research on how the three sustainability pillars (environmental, economic and social) are evaluated and managed in a multi-criteria perspective, to design future research agenda.

2. Motivation

2.1 Distributed energy generation

Distributed energy generation (DEG) is not a new approach, based both on conventional and renewable energy sources (RES) (Ackermann, Andersonn and Soder, 2001; Chicco and Mancarella, 2009). On the other hand, the concept of DEG is evolving driven by technical progresses, economic and political factors (Jaina et al, 2017).

In general terms, DEG refers to small to medium scale modular energy generation units (Alanne and Saari, 2006), typically ranging from few kW to tens of MW. DEG systems can be sized to meet specific demand needs and installed on site, aiming at utilizing local fuels. According to Ackermann et al. (2001), distributed generation refers to an electric power connected directly to the distribution network or on the customer side of the meter. Associated demand-side resources (load management systems, energy efficiency options) can contribute to reduce customer demand and influence the electricity supply from the distribution network. Efficient and cost-effective storage solutions can work as load levelling devices.

The advantages of this configuration are manifold, such as high modularity and flexibility.

DEG configuration allows both the grid modernization, through smart grid solutions, and the integration of renewables (e.g. wind turbines, solar thermal and photovoltaics (PV), micro-hydro generators and biomass generators), ensuring grid stability and resilience, key points mainly for industry (Pepermans et al., 2005).

2.2 Multi-criteria analysis

Multi-criteria analysis methods are widely used to manage complex systems involving large amounts of information, conflicting objectives and multiple actors.

These techniques are successfully applied in the public sector (e.g. Lolli et al., 2017; Lolli et al., 2016) as well as to manage industrial complex systems and renewable energy industry (San Cristóbal Mateo, 2012).

Moreover, they have become increasingly popular in designing renewables integration in the energy market substituting simpler approaches (such as cost–benefit or cost-effectiveness approach and energy ecological footprint) because of the multi-dimensionality of the sustainability goals (Løken, 2007) and the different points of view and interests that the multi-actors involved bring along (Pohekar and Ramachandran, 2004).

A typical set of evaluation criteria of energy supply systems has been compiled by Wang et al. (2009): the criteria used in the literatures usually are categorized as technical, economic, environmental and social, depending on the objectives of the study.

2.3 Review objectives

Most research cases dealing with distributed renewable energy generation in a multi-criteria analysis approach mainly tend to evaluate which is the most suitable technique to handle the case, or to focus on either environmental or economic or social aspects. However, the consideration of all three sustainability pillars is required for an advantageous strategy to drive the transition to a low-emissions energy system.

This literature review has been conducted with the aim of collecting a comprehensive set of criteria suitable for evaluating the sustainability of the distributed energy generation system integrating renewables.

The following questions drove the investigation, to identify future research pathways:

- Do the criteria usually selected in recent investigation papers cover all the three key sustainability dimensions of the distributed renewable energy generation scheme?

- How the used criteria account for the sustainability of the innovations introduced by distributed renewable energy generation?

3. Methodology

The review on relevant literature started from the definition of keywords for online searches in academic journal articles. The search has been performed using online databases Science Direct and Web of Science. In the first step, a list of relevant keywords has been selected based on the main elements of the topic under study, namely the "multi-criteria analysis" applied to "distributed energy generation", integrating "renewable sources of energy" in a "sustainability" comprehensive view. After a first exploration of available literature based on the selected keywords, the research team identified the set of keywords that better fit the papers that fulfill the review objectives. Some review papers presenting the state-of-the-art in adjacent research fields have been also considered.

The literature analysis was limited to the period following 2010, when the technological advancements, the declining prices of RES and the fast growing of the RES installed capacity, oriented the studies on energy transition pathways to a high share of renewables to DEG configuration.

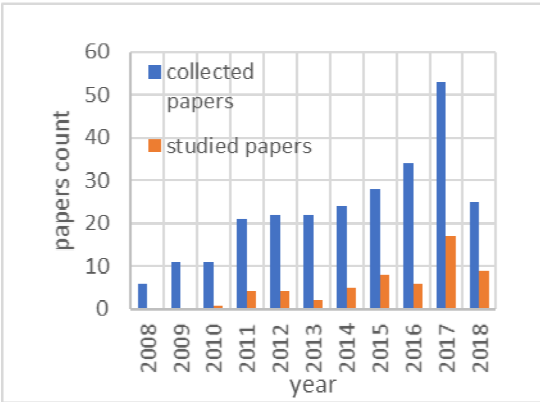

Figure 1: distribution of the publication dates for the papers applying multi-criteria analysis to distributed renewable energy generation (blue bars) and for the reviewed ones (orange bars).

A total number of 257 papers were initially collected; the abstracts of the collected papers were analyzed to exclude non-relevant ones. Most papers were excluded during this step since they mainly focus on the analysis of the technical feasibility of DEG configuration or they analyze the better multi-criteria method to approach a specific case. After the examination, 56 papers were selected as they fit the purpose of this study. The distribution of publication dates for the collected papers and the reviewed ones are reported in the Figure 1.

A representative set of sustainability criteria have been compiled and discussed.

4. Discussion

Sustainability is a key aspect of an energy project. Sustainability issues have been widely analyzed both related to renewable energy integration in the grid (Banos et al., 2011) and to distributed energy generation (Alanne and Saari, 2006). A distributed energy system guarantees reliability, scalability and cost-effectiveness, and is environmentally friendly (Alanne and Saari, 2006; Verbong and Geels, 2010). On the other hand, small scale renewable energy systems have long been considered as environmentally and social sustainable solutions (Rae and Bradley, 2012) and are now economically affordable.

The transition from a centralized energy generation system to a distributed one requires a change in the design and management approach, concerning a complex multi-dimensional system. The need to handle simultaneously technical, economic, social and environmental issues lead to the use of multi-criteria analyses tools to formulate and solve the configuration problem addressing multiple objectives and including the most of criteria that better fits the sustainability goals to be reached.

From the online search resulted that multi-criteria analysis have been applied to planning renewable energy sources integration since the earliest 2000 (Figure 2, orange dots).

The researches, often case studies, focused mainly on techno-economic (Østergaard, 2009) and regulatory issues (as in Matulaitis et al., 2016). Tools for supporting decision-making in energy planning processes are developed for example by Tsoutsos et al. (2009): alternative RES technology are assessed (considering both stand-alone and grid connected systems) against economic, technical, environmental and social criteria.

Environmental impact on specific areas was evaluated also through land use criteria and some social criteria were introduced as in Mourmouris and Potolias (2013).

From the last decade the transition to a distributed renewable energy generation scheme has been widely evaluated as the most favorable solution (Singh and Parida, 2018) to integrate a high share of renewables in the energy production and distribution system. A fast-growing number of research papers dealing with distributed generation and RES have been found from year 2010 (Figure 2, blue dots). These findings are consistent with the trend of the RES uptake process.

In many countries the cost of renewables is getting closer to fossil fuel parity and many renewables technologies are by now mature (Antonini et al., 2015) pushing renewables deployment, while large renewables power plants pose some issues related, for example, to land grabbing, noise or visual impacts and massive investments in infrastructures (Scheidel and Sorman, 2012).

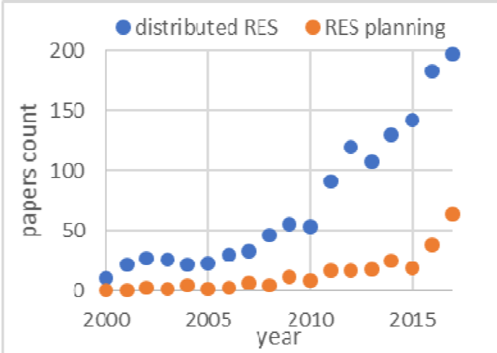

Figure 2: Trend in papers dealing with "distributed RES" (blue dots) and "RES planning" publication (orange dots).

On the other hand, recent technological advancements in storage solutions and performance as well as the massive improvements in ICT allow now smart grid architectures including renewable sources (Anaya and Pollitt, 2017). Bi-directional energy trading is enabled and demand side management (DSM) can now be considered a way to enhance customers service, allowing the reduction of peak-to-average ratio of the power system and the energy costs for consumers (Liu and Hsu, 2018). Available advanced sensing and digitization allow to match supply and demand, facilitating energy savings.

The new bi-directional energy system brings about the concept of "prosumer", the energy user (household, community or industry) that is also an energy producer (Green and Newman, 2017). The number of stakeholders involved in the distributed renewable energy approach is then bigger than it was in the centralized system.

Multi-criteria analysis methods respond well to this increased complexity (Ehsan and Yang, 2018; Kumar et al., 2017) and are used as support in decision making processes (Cardoso de Lima et al., 2018). However, a great effort is still committed to techno-economic optimal planning of distributed renewable energy generation in terms of choosing the best technology alternative (or technologies combination) (i.e. Yuan et al., 2018), optimal size, location and power factor of the generation units, aiming at maximizing DEG penetration and costs savings (Tanwar and Khatod, 2017).

Many of the reviewed papers deal with the choice and application of a specific multi-criteria method to solve a local problem or to design a local energy strategy (as in Neves et al., 2018); case studies are mainly related to regional and rural applications (Rojas-Zerpa and Yusta, 2015).

At urban level the distributed generation can foster the integration of renewables. The urban energy systems are developed at community level, where the involvement of the consumers (residential, commercial and industrial energy users) as stakeholders becomes relevant (as in Manfren et al., 2011), many conflicts can arise, and decision-making processes can be supported by multi-criteria decision analysis methods (Cajot et al., 2017).

Abotah and Daim (2017) consider policy aspects to evaluate the effectiveness of energy policy instruments in pushing the adoption of renewable energy sources, also through distributed generation. Five perspectives have been considered in the study: economic feasibility improvement, technical system development (including facilitating grid access and improving RES integration capabilities), social acceptance including increased awareness and knowledge, political and environmental protection.

Multi-criteria analysis methods are going to be applied also to some emerging concepts related to the distributed renewable energy generation such as energy hubs (multi-carrier generation systems) integrating renewables, as in Perera et al. (2017), where a study on rural electrification project for a small model village is presented; resource management in renewable assisted microgrids (Naz et al., 2017); and virtual power plants, aggregating distributed generation units (Sowa et al., 2014).

4.1 Criteria definition

In the Table 1 the criteria extrapolated from reviewed literature are summarized, in relation to the three sustainability pillars.

A good agreement on the criteria definition have been found among papers, while some specific sub-criteria or indicators are linked to the case studied. Some criteria are quantitative, other qualitative and depend on subjective evaluation. Here, the technical aspects are included in the economic dimensions, since they are evaluated as costs or can be easily converted in associated costs.

The criteria and indicators are mainly selected starting from literature (Wu et al., 2018) and from the standard criteria set for energy planning, as summarized in Wang et al. (2009).

Only in Cardoso de Lima et al. (2018), among the reviewed papers, the set of criteria has been created putting in relation the relevant characteristics of distributed generation to sustainability indicators, identifying the interconnection factors. The assumed DEG relevant characteristics are:

- Use of energy resource available on site
- Electricity production near consumption centers
- Availability of electricity to supply local demand
- Use of smaller generation units

4.2 Results and analysis

The criteria listed in Table 1 are hereinafter described and commented. In column 3 the percentage of papers, among those analysed, considering the corresponding criterion is reported.

The *environmental sustainability* of an energy generation plant is a key requirement, mostly at local level. DEG configuration and the chosen RES technology affect environmental impacts. In the reviewed papers the environmental impacts are evaluated through:

- air and noise pollution: greenhouse gas (GHG) emissions (e.g. carbon dioxide) causing global warming and other pollutants hazardous to the health are considered (nitrogen oxides, sulphur dioxide and particulate matter). Smells and noise can influence people's work and life. This criterion can evaluate both the GHG emission reduction and the produced emissions by some renewables, such as biomass and wind turbines.

- land use is the area occupied by the generation unit. The DEG configuration allows a substantial reduction of land use respect to centralized plants (also reducing the economic impact); when dealing with biomass (i.e. crops, wood), the competition with land used for food should be considered.

Table 1: MCA criteria from reviewed literature

Sustainability pillar	Criteria	% of use
Environmental	Pollution (air – CO_2, NO_x, SO_2, PM10-PM2.5 emissions, noise), odours	80.4
	Land use	55.4
	Impact on ecosystems	44.6
	Impact on landscape	32.1
	Need of waste disposal	12.5
	Physiological effects	17.9
Economic (techno-economic)	Net Present Value	7.1
	Capital and variable costs (O&M)	62.5
	Reduction of network connection costs/ distance to user	17.9
	Conventional fuel savings	6.2
	Payback period	12.5
	Service life	6.2
	Electricity costs	25
	Availability and density of the source of energy	37.5
	Technology efficiency	32.1
	Innovation	17.9
Social	Social acceptance	44.6
	Job creation	55.4
	Sufficient supply to meet basic needs	17.9
	Social benefits	44.6
	Improvement of educational level	12.5
	Safeguards	12.5
	Advanced performance	5.4

- impact on landscape: visual impact is relevant also for small energy generation units that can be located in picturesque urban or natural spaces

- impact on ecosystems: though water consumption of distributed RES is generally low, the quality of water can be impacted, both in terms of temperature variation and contamination, in hydro power, geothermal, biomass facilities; biodiversity can also be negatively impacted by habitat disturbance and/or wildlife activity disruption: wind turbines can interfere with bird migration paths, hydro power can disrupt fish habitat, and biomass use can reduce the organics matter returned to soil.

- need of waste disposal: it refers to some RES technologies such as biomass

- Hartmann et al. (2017), under environmental aspects, consider also "physiological effects", namely the lost years per generated energy (evaluated in [c€/kWh]), as human health indicator.

The *economic* sustainability assessment must allow the local communities and energy stakeholders to pursue economic growth collectively and satisfy essential needs. In the reviewed papers, economic aspects of a project are evaluated through:

- Net Present Value (each cash inflow/outflow is discounted back to its present value).

- Capital costs and the operating and maintenance (O&M) costs, that include the project investment (mechanical equipment and electrical connections, technological and infrastructure installation, engineering services), the cash flows and the variable costs during plant running (including the salaries of operators involved in maintenance operations).

- Innovation potential of the project in terms of patents developed and potential market (i.e. new chain of energy businesses, alternatively evaluated under the social pillar).

Some techno-economic aspects evaluated in a sustainability view are here reported:

- reduction of network connection costs/ distance to user: the distance to the main distribution grid and the related connection costs has great relevance in the cost of implementation of the generation unit

- Conventional fuel savings: the total quantity of fossil fuels replaced by electricity generation by RES can be calculated

- electricity costs, in terms of LCOE, depends on the RES chosen

- Payback period, i.e. the period of time required for the return of an investment to repay the sum of the initial investment, depends on the RES technology chosen (and from availability and density of the source of energy), storage and demand management options;

- service life: is the expected operating period of time during which the plant will produce energy (or the acceptable period of use in service) and depends on the chosen technologies

- Technology efficiency rates how much useful energy can be obtained given the availability and density of the source of energy, and it determines the electricity generation cost

- Availability and density of the source of energy (sun radiation, wind speed, …): it influences the choice of the proper RES technology.

Social sustainability pertains equality and basic necessities fulfillment as well as social progress of the involved community. In the reviewed papers social aspects are evaluated through:

- Social acceptance, that expresses the overview of opinions related to the energy systems: the local character of DEG projects makes essential a favorable reception from the residents.

- Job creation: energy supply systems employ people during their life cycle

- Sufficient supply to meet basic needs draws attention to the need for equitable energy availability, to promote socioeconomic development and quality of life

- social benefits represent local development determined by the energy project (new chain of energy businesses, new industrial regions, etc.; it can include job creation, if not make explicit); the allowed by the new energy system savings (i.e. euros saved per household per year) are considered by some authors

- improvement of educational level of the community where DEG system is installed is foreseen, due to the need for skilled professionals to be engaged in installation and O&M tasks that should entail local workers training

- safeguards, express whether the system is safe to surrounding and people or not

- advanced performance: express whether the system or technology is advanced now and will be more perfect in the future

As can be seen in the table 1, some of the criteria are most widely used. Environmental impacts are mainly evaluated through air pollution, while local ecosystems and landscape integrity, and human health safeguard are arguably implicitly included in pollution effects. Among economic criteria, the most considered criterion is the cost of project investment and O&M (62.5%); the local availability of the source of energy is considered only by the 37.5% of the authors. Social impacts on local communities are mainly evaluated through job creation (55%), but also social acceptance and social benefits are considered important indicators (44.6%).

5. Open issues and research directions

The performed literature review highlighted some open issues in the research investigating the sustainability of the distributed renewable energy generation configuration. Driven by the questions expressed in the paragraph 2, we argue that the sustainability evaluation of the DEG scheme for the integration of renewables through multi-criteria analysis is still unbalanced towards techno-economic aspects.

Environmental aspects could be better investigated including life-cycle evaluation of environmental impacts of the considered technologies. In fact, while renewable energy systems have no, or minimal, negative impact on the environment while operating, a more comprehensive view of their sustainability is desirable as it can foster an increased awareness of the consumers as well as of the other stakeholders regarding the complexity of the GHG emissions reduction goals.

Social aspects should include the evaluation of the level of empowerment of energy consumers facilitated by the DEG configuration, considering the possible and highly beneficial active role that they can play in the transition to a more sustainable energy system.

From the performed analysis, the need arises for a more focused correlation with the DEG peculiar characteristics when choosing the criteria. Although standard criteria used in energy planning can be considered a good starting point for sustainability evaluation, a more precise correlation with the DEG configuration and its more innovative aspects should be examined. Some inconsistencies have been found in used DEG definition, also in the most recently published papers: despite the wide debate on DEG definition and paradigm change (see for example Singh and Parida, 2018), in some cases stand-alone systems are still treated as distributed generation (Rojas-Zerpa and Yusta, 2015). Moreover, in our view, some new opportunities offered by DEG configuration, such as energy savings aspects and system reliability improvements, are still under investigated in a comprehensive sustainability view through multi-criteria analysis.

6. Conclusions

The transition to a low-emission energy system with a high share of renewable energy sources, can be sped up by renewables integration through distributed energy generation.

The multi-dimensionality of sustainability goals set by energy transition and the complexity of DEG systems, that involves a plurality of actors, can successfully be managed in a multi-criteria analysis perspective.

Our review highlighted how, although multi-criteria analysis methods have been long used to support energy planning, the shift to a distributed renewable energy generation system requires a more precise focus on the peculiarity of this configuration to build up a more comprehensive sustainability view. More specific criteria should be considered both to design an exhaustive sustainability picture of the DEG approach and to support decision-making in case projects.

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